# Tertiary Non-marine Diatoms from Eastern Australia: Palaeoecological Interpretation and Biostratigraphy

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THOMAS, D. P., & GOULD, R. E. Tertiary non-marine diatoms from eastern Australia: palaeoecological interpretation and biostratigraphy. *Proc. Linn. Soc. N.S.W.* 105 (1), (1980) 1981: 53-63.

Late Oligocene to Middle Miocene non-marine diatomites from eleven localities in New South Wales and south-eastern Queensland are considered to be of lacustrine origin, being formed in eutrophic, slightly alkaline, freshwaters. Weathering of associated contemporaneous basaltic lavas probably contributed to the favourable water quality. Evidence from varves in some of the diatomites suggests the life of each water body was relatively short in comparison to the accuracy with which the geological age of a deposit can be estimated. Planktonic, epipelic, and epiphytic taxa were represented at all localities; some assemblages were largely planktonic while others were composed mostly of benthic taxa. It is concluded that similarity between the non-marine diatom floras indicates similar conditions prevailed at the sites of deposition, and this environmental control of the floras over-rides any other biostratigraphic conclusions.

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## INTRODUCTION

Diatoms are known to have inhabited non-marine waters at least since Late Eocene (Lohman and Andrews, 1968) with the most probable origin of these freshwater diatoms being the invasion of non-marine environments by marine taxa (Van Landingham, 1967). As the earliest known non-marine floras are taxonomically quite diverse, perhaps earlier records are limited either by the absence of conditions allowing deposition of diatomite or by the subsequent reversion of the metastable opaline silica of which the diatom frustules are composed. Occurrence of fossil marine diatoms extends from at least the late Early Cretaceous (Ross, 1967; Haig and Barnbaum, 1978), well before the first appearance of non-marine taxa.

Because of their sensitivity to the ambient environment in which they grow, the value of extant non-marine diatom floras as indicators of environmental conditions has been given prominence of late (e.g. Patrick, 1977). However in many previous studies of fossil non-marine diatom floras (e.g. Andrews, 1971; Abbott and Van Landingham, 1972), while details of water quality were derived from knowledge of the represented taxa, the complete picture of the depositional environment from both geological and biological viewpoints (see Conger, 1942) was not as well covered as might be desired. We acknowledge that such an ideally complete interpretation is not always possible since all relevant information may be unobtainable, and this applies to several localities involved in the present study, but we have tried to integrate all information available over the range of deposits investigated. Of course contraints on any environmental interpretation from fossils, dependent on comparison with living examples, include the sometimes incomplete or conflicting data available for extant taxa and the need to assess if any changes have taken place from the past to the present.

Details of diatom occurrences and palaeoecological interpretations for some eastern Australian diatomites have been previously presented by Skvortzov (1937), Crespin (1947), Tindale (1953), Gill (1953), and Herbert (1968). Information on the taxa discussed in this paper has been presented previously (Thomas and Gould, 1981).

## Materials and Methods

Diatomite samples were obtained and prepared as outlined by Thomas and Gould (1981). The taxa present in each sample and their relative abundances were noted.

The qualitative system of relative abundance recommended by Andrews (1972) was adopted. This was considered the best method for handling numerous samples at a level of information commensurate with the probable degree of preservation of the original diatom flora. Each taxon was thus rated: 1, dominant, numerous specimens in all fields of view. 2, abundant, at least one specimen in every field of view. 3, common, at least one specimen in every 2-5 fields of view. 4, frequent, several specimens on entire slide. 5, rare, one or two specimens on entire slide. When studying preparations of a microfossil flora, what is observed is generally an integrated sample of the remnants of the original assemblage. In the case of diatoms, some species, due to thicker frustules or having suffered low predation rates, as well as those with a greater initial abundance, are likely to be better represented in the subsequent fossil deposit than other species. Thus the qualitative method proposed by Andrews (1972) was considered better suited to the purpose than any semiquantitative method, avoiding the trap of trying to read too much into variations in the data.

## Localities

The eleven localities in New South Wales and south-eastern Queensland from which samples were investigated have been listed together with pertinent geological information by Thomas and Gould (1981). All deposits are of shallow lacustrine origin and are generally associated with basaltic lavas and tuffs. They range in age from Late Oligocene to Middle Miocene. Some ideas, derived from available geological exposures, on the physiography of the various lakes prior to the outpouring of the overlying basalts, are discussed here, including an estimate of the initial minium depth.

*West Haldon.* Small lake, at least 4 m deep but most likely 8-9 m, probably relatively sheltered, on north facing slope of the lower lavas of the Main Range Volcanics.

*Black Duck Creek.* Small lake, at least 4 m but up to 6 m deep in centre, probably exposed position, on eastern flanks of lower lava flows of Main Range Volcanics.

*Tintenbar.* Small lake, at least 5 m deep in centre, shallowing to less than 0.3 m, exposed, on the south-eastern side of the Tweed Shield Volcano.

*Wyrallah.* Small lake, at least 2.5 m deep, exposed, on the southern slopes of the Tweed Shield Volcano.

*Bells Mountain.* Larger (though still small) lake, 6-12 m deep, exposed, to the east of the Nandewar Volcano.

*Nandewar Range.* Larger, though still small, lake, at least 8 m deep, exposed, on the south-eastern side of the Nandewar Volcano.

*Paddy McCullochs Mountain.* Larger lake, occurring in depression in Jurassic sediments, at least 30 m deep, on eastern side of Warrumbungle Volcano.

*Chalk Mountain.* Larger lake, at least 14-17 m deep, exposed, on north-eastern flank of Warrumbungle Volcano.

TABLE 1

Distribution and number of taxa in some extant and fossil diatom assemblages from eastern Australia with respect to families.

| | *Murray R. Pool, S.A.* | *Lake Picton, Tas.* | *Lillicur, Vic.* | *Bowan Downs* | *Middle Flat* | *Wantialaba Ck* | *Chalk Mt.* | *Paddy McCullochs Mt.* | *Bells Mt.* | *Nandewar Ra.* | *Wyrallah* | *Tintenbar* | *West Haldon* | *Black Duck Ck* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Suborder COSCINODISCINEAE | | | | | | | | | | | | | | |
| Fam. MELOSIRACEAE | 3 | 1 | – | 3 | 1 | 1 | 1 | 1 | 3 | 3 | 2 | 2 | 2 | 2 |
| Fam. THALASSIOSIRACEAE | 2 | 1 | – | – | – | – | – | – | – | – | – | – | – | – |
| Suborder ARAPHIDINEAE | | | | | | | | | | | | | | |
| Fam. DIATOMACEAE | 3 | – | 3 | 2 | 2 | 1 | 1 | – | 2 | 3 | 3 | 3 | 4 | – |
| Suborder RAPHIDIOIDINEAE | | | | | | | | | | | | | | |
| Fam. EUNOTIACEAE | 1 | 1 | 1 | 1 | – | 1 | 1 | – | 1 | 1 | 1 | 1 | 1 | 1 |
| Suborder MONORAPHIDINEAE | | | | | | | | | | | | | | |
| Fam. ACHNANTHACEAE | 2 | – | 2 | – | – | – | – | – | 1 | 1 | 1 | 2 | 5 | – |
| Suborder BIRAPHIDINEAE | | | | | | | | | | | | | | |
| Fam. NAVICULACEAE | 7 | 1 | 3 | 4 | 2 | 2 | 2 | 1 | 4 | 4 | 4 | 7 | 8 | 1 |
| Fam. CYMBELLACEAE | 3 | 1 | 2 | 3 | 1 | 1 | 2 | – | 2 | 3 | 2 | 3 | 3 | 3 |
| Fam. NITZSCHIACEAE | 5 | – | 1 | 1 | – | – | – | – | – | – | – | – | – | – |
| Fam. EPITHEMIACEAE | 1 | – | 1 | – | – | – | – | – | – | – | – | – | – | – |
| Total Taxa | 27 | 5 | 13 | 14 | 6 | 6 | 7 | 2 | 13 | 15 | 13 | 18 | 23 | 7 |
| Total Genera | 17 | 5 | 11 | 10 | 5 | 6 | 7 | 2 | 8 | 10 | 10 | 10 | 10 | 5 |
| Estimated Age (my) | 0 | 0 | 2.5 | 11-12 | ? | 14-15 | 15-16 | 15-16 | 18 | 18 | 21 | 21 | 23-24 | 23-24 |

*Wantialaba Creek.* Very small depressions in flows and tuffs of southern side of Warrumbungle Volcano.

*Bowan Downs.* Larger lake, at least 6 m deep, exposed on south-western flank of Canobolas Volcanic Complex.

*Middle Flat.* Larger lake, situated in depression in Palaeozoic siliceous sediments, at least 9-16 m deep, exposed position, just beyond the northern flank of the Monaro Province lavas.

In addition to the eastern Australian diatomite samples which form the basis of the study (see Thomas and Gould, 1981), two samples taken from living assemblages were noted to aid as reference material. One sample came from the oligotrophic Lake Picton, Tasmania, and the other from an eutrophic pool beside the Murray River, near Mannum, South Australia. Both samples were cleared with concentrated nitric acid, after the method of Crawford (1971), and mounted on cover glasses in similar fashion to the fossil material.

Samples from the non-marine diatomite deposit near Lillicur, Victoria, associated with basalts of the Newer Volcanics that have been assigned Late Pliocene ages of approximately 2.5 – 2 m.y. in nearby regions (Aziz-ur-Rahman and McDougall, 1972), were added to fill in the gap between the Miocene deposits and the Recent samples (see Table 1).

## Estimated Rates of Deposition

As some of the diatomites exhibit seasonal varves, which we assume to be annual increments of deposition (see Round, 1964), the rate of accumulation for the various deposits can be estimated. Some of the best preserved varves come from the West Haldon deposit (Fig. 1A) where they average 20-30 varves per centimetre or an annual increment of 0.33 — 0.5 mm. The West Haldon deposit has a measured thickness of 4-5m representing some 8,000-10,000/12,000-15,000 years deposition. Where varves occur at other localities, e.g. Black Duck Creek, and Chalk Mountain, the varves are of similar thickness averaging 0.33-0.5 mm.

This information regarding the time taken for the formation of any one diatomite deposit, being evidently restricted to tens of thousands of years, carries with it the possibility that ponds or lakes considered to be of similar geological age may not necessarily be precisely contemporaneous.

## Palaeoecological and Biostratigraphic Interpretation

The environmental requirements for some of the taxa present in the eastern Australian diatomites that we examined have been elucidated for examples from the Miocene of North America by Abbott and Van Landingham (1972) and for living eastern Australian diatoms by Foged (1978). From their information we deduce that the water bodies in which the Australian diatomites formed were eutrophic, slightly alkaline, and fresh.

In general, for freshwater diatoms in aquatic habitats any one of several factors may limit diatom production (see Patrick, 1977). Presence of nutrients such as nitrogen and phosphorus are important for maximum development while potassium and calcium carbonate may also play a part; silica must be present for some diatoms

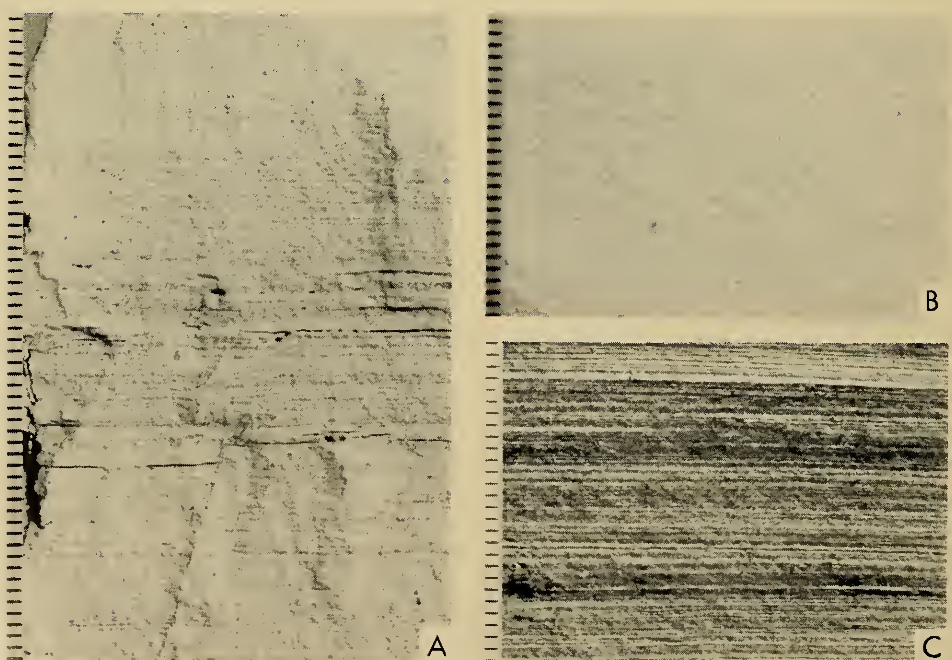



*Fig. 1.* Diatomite samples viewed in sections approximately perpendicular to bedding; scales in millimetres. A, sample from West Haldon, showing depositional varves. **B**, massive diatomite from Milne's Hill, Tintenbar. C, varved diatomite from the Black Duck Creek deposit; organic matter is responsible for the dark colouration.

to occur in abundance but is not a major limiting factor unless completely absent, and metals can be important in determining which species are present. Different concentrations of these substances result in the development of different diatom floras. Weathering of the alkali basaltic rocks that are characteristically associated with Australian non-marine diatomite deposits would provide most of these substances apart from nitrogen and analyses of these rocks indicate high phosphorus contents (Wilkinson *et al.*, 1969).

The climate in eastern Australia during the Oligocene-Miocene time of diatomite deposition was equable with a very high rainfall and stable temperatures (Martin, 1978). The reconstructed palaeolatitudes during this time show a gradual northward drift away from Antarctica, the region containing the diatomites in question being approximately 36°-48°S in the Late Eocene and 28°-38°S in the Late Miocene (see Smith and Briden, 1977) compared to the present day 27°-37°S. The deposits are almost always situated on the northern, eastern, or southern slopes of approximately contemporaneous volcanic complexes, one exception being Bowan Downs which is on the south-western slopes of Mount Canobolas (see Thomas and Gould, 1981, fig. 1); the localities would thus normally have lain in the path of the prevailing moisture-laden winds from the Pacific Ocean in contrast to the western slopes which would presumably have been rain-shadow areas.

The geometry of the diatomite deposits indicates they were formed in relatively shallow lakes. Apart from the varves exhibited at some localities, and fossils of fish, leaves, and occasionally wood (see Herbert, 1968), the diatomite itself is devoid of sedimentary structures although containing interbedded claystone, sandstone, and tuffaceous layers. Wind-driven waves and currents are the important causes of water movement and mixing in lakes (Reading, 1978); the effects of this can be seen in the diatomite at different localities. In some the annual layers of diatom sediment, or varves, were undisturbed by mixing when the water was greater than 3-4 m in depth, but the sediments deposited above this depth were well mixed, presenting a massive appearance, in agreement with the findings of Round (1964). An example of this is the Black Duck Creek deposit in which the varved layering in the lower part of the section (Fig. 1C) is in contrast to the upper 3.5 m of massive diatomite; the lake in this case had filled up, or at least ceased deposition of diatomite due to an influx of clay with an uppermost carbonaceous layer, prior to being capped by lava. At West Haldon the water body was either sufficiently deep or well protected, or both, for varves to be preserved throughout the upper 4-5 m exposed by the mine (Fig. 1A). At Bells Mountain the lake was bigger, being at least 1 km long, and perhaps even connected to the Nandewar Range site some distance to the west, so presenting a larger fetch for the wind; here, except for the more dense interbedded sandstone and clay layers, the diatomite is mostly massive to a depth of at least 12 m from the base of the overlying lava. Many of the varved layers at Black Duck Creek (Fig. 1C) and Chalk Mountain still contain a quantity of organic matter resulting in a brownish, grey, or almost black appearance; this organic matter probably originated with the diatoms as outlined by Conger (1942) but has not been leached, decomposed or oxidized to produce the normal bleached white colour.

Thus there was likely to have been considerable between-site differences in environment at the time of deposition and this must be taken into account when evaluating the palaeohabitat and biostratigraphic significance of species presence and absence.

Planktonic, epipelic and epiphytic taxa are present in all the localities thus implying that the water bodies were shallow enough to support benthic macrophytes and microphytes, or that floating algae or macrophytes were present, or the lakes had

TABLE 2

Distribution of taxa in eastern Australian diatomite localities. Key: +, present in at least one sample; + +, dominant in at least one sample.

| | *Bowan Downs* | *Middle Flat* | *Wantialaba Ck* | *Chalk Mt.* | *Paddy McCullochs Mt.* | *Bells Mt.* | *Nandewar Ra.* | *Wyrallah* | *Tintenbar* | *West Haldon* | *Black Duck Ck* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Nitzschia scalaris* | + | | | | | | | | | | |
| *Melosira granulata* | ++ | ++ | ++ | ++ | ++ | ++ | ++ | ++ | ++ | + | ++ |
| *Gomphonema intricatum* | + | ++ | + | + | | | + | + | + | + | + |
| *Fragilaria construens* var. *venter* | + | + | + | + | | + | ++ | ++ | + | ++ | + |
| *Pinnularia* sp. af. *major* | + | + | + | + | + | + | + | + | ++ | + | + |
| *Stauroneis frauenfeldiana* | + | + | | + | | + | + | + | + | + | |
| *Eunotia pectinalis* | + | | + | + | | + | + | + | + | + | + |
| *Cymbella ventricosa* | + | | | + | | + | + | | + | ++ | + |
| *Navicula amphibola* | + | | + | | | | + | + | + | + | |
| *Melosira* sp. A | + | | | | | ++ | + | | | | |
| *Melosira undulata* var. *spiralis* | + | | | | | + | | + | + | + | + |
| *Cymbella cistula* var. *maculata* | + | | | | | + | + | + | + | ++ | + |
| *Pinnularia graciloides* | + | | | | | + | + | | + | + | |
| *Synedra ulna* | + | | | | | | | | | + | |
| *Fragilaria leptostauron* | | + | | | | | | | | | |
| *Fragilaria leptostauron* var. *dubia* | | | | | | + | + | | | | |
| *Achnanthes* sp. af. *lapidosa* | | | | | | + | + | + | + | + | |
| *Navicula seminuloides* | | | | | | + | | + | + | ++ | |
| *Melosira granulata* var. *curvata* | | | | | | | + | | | | |
| Cf. *Synedra* | | | | | | | + | + | + | + | |
| *Fragilaria lapponica* | | | | | | | | + | + | + | |
| *Navicula naumannii* | | | | | | | | | + | | |
| *Achnanthes* sp. af. *atomus* | | | | | | | | | + | + | |
| *Navicula* sp. af. *perpusilla* | | | | | | | | | + | + | |
| *Navicula seminuloides* var. *rhombica* | | | | | | | | | | ++ | |
| *Achnanthes* sp. A | | | | | | | | | | + | |
| *Achnanthes lanceolata* | | | | | | | | | | + | |
| *Achnanthes* sp. B | | | | | | | | | | + | |
| *Navicula* sp. af. *laterostrata* | | | | | | | | | | + | |
| Total taxa | 14 | 6 | 6 | 7 | 2 | 13 | 15 | 13 | 18 | 23 | 7 |
| Total genera | 10 | 5 | 6 | 7 | 2 | 8 | 10 | 10 | 10 | 10 | 5 |
| Estimated Age (my) | 11-12 | ? | 14-15 | 15-16 | 15-16 | 18 | 18 | 21 | 21 | 23-24 | 23-24 |

peripheral or upstream shallows and marshes from which the benthic diatoms were washed into the area of deposition. For example, the majority of the species represented in the diverse West Haldon assemblage are benthic taxa which, if found in the plankton, would usually be there adventitiously. The difference between the West Haldon assemblage and that of Middle Flat, one of the least diverse localities, is the relative contribution of the benthic (e.g. *Cymbella* spp.) and largely planktonic (e.g. *Melosira granulata*) taxa respectively. *Melosira granulata* is presently distributed world wide in euthrophic freshwaters and was characterized by Abbott and Van Landingham (1972) and Foged (1978) as alkaliphilous, mesosaprobic, oligohalo-

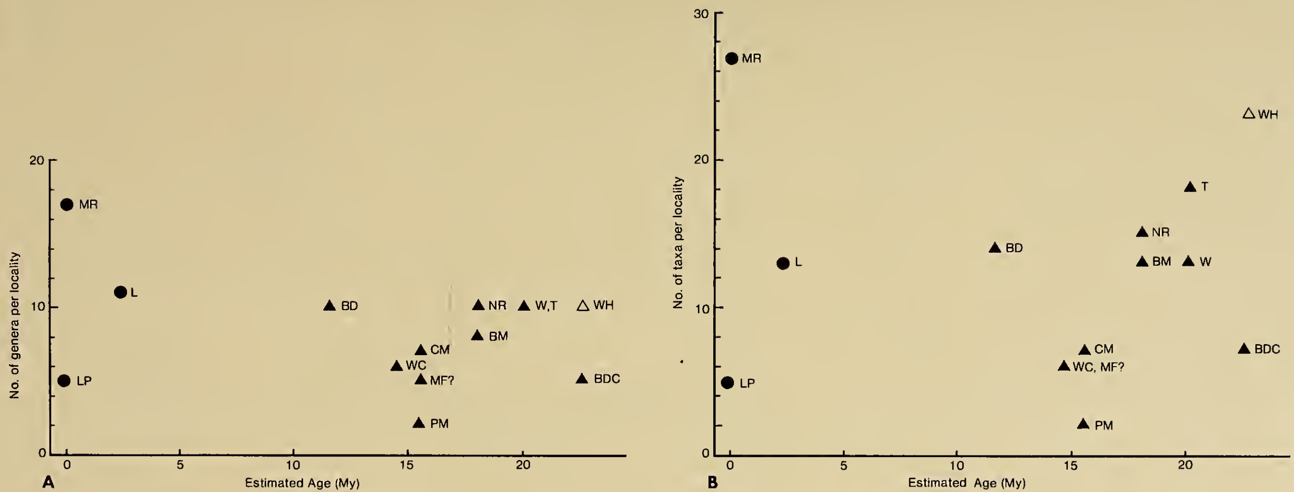



*Fig. 2.* **A**, scattergram of the number of diatom genera represented at each locality compared to the estimated geological age. **B**, scattergram of the total number of taxa represented at each locality compared to the estimated geological age. Key: BD, Bowan Downs; BDC, Black Duck Creek; BM, Bells Mountain, CM, Chalk Mountain; L, Lillicur; LP, Lake Picton; MF, Middle Flat; MR, Murray River pool near Mannum; NR, Nandewar Range; PM, Paddy McCullochs Mountain; T, Tintenbar; W, Wyrallah; WC, Wantialaba Creek; WH, West Haldon; ●, additional information outside of study area; ▲, locality where *Melosira granulata* was dominant in some samples; △, locality where *Cymbella* spp. were dominant in some samples.

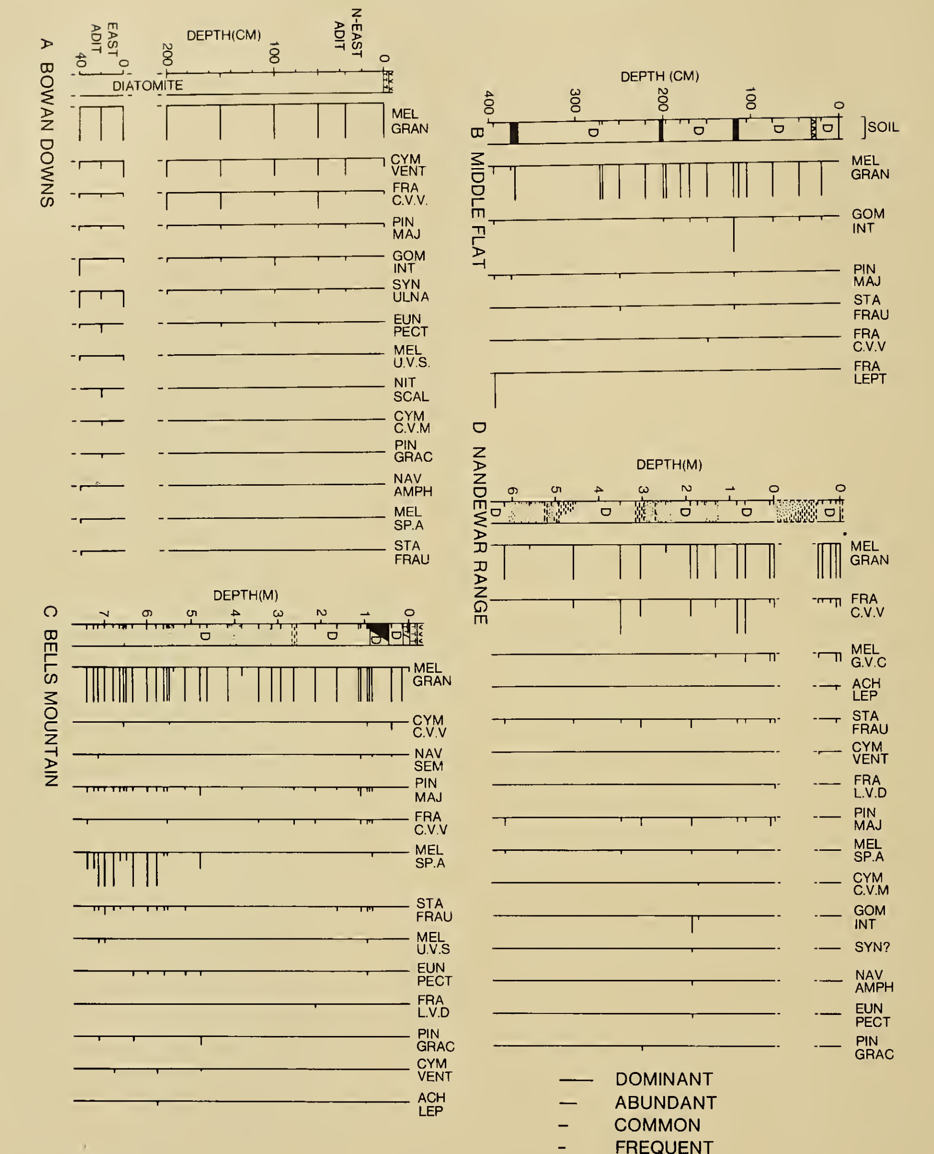
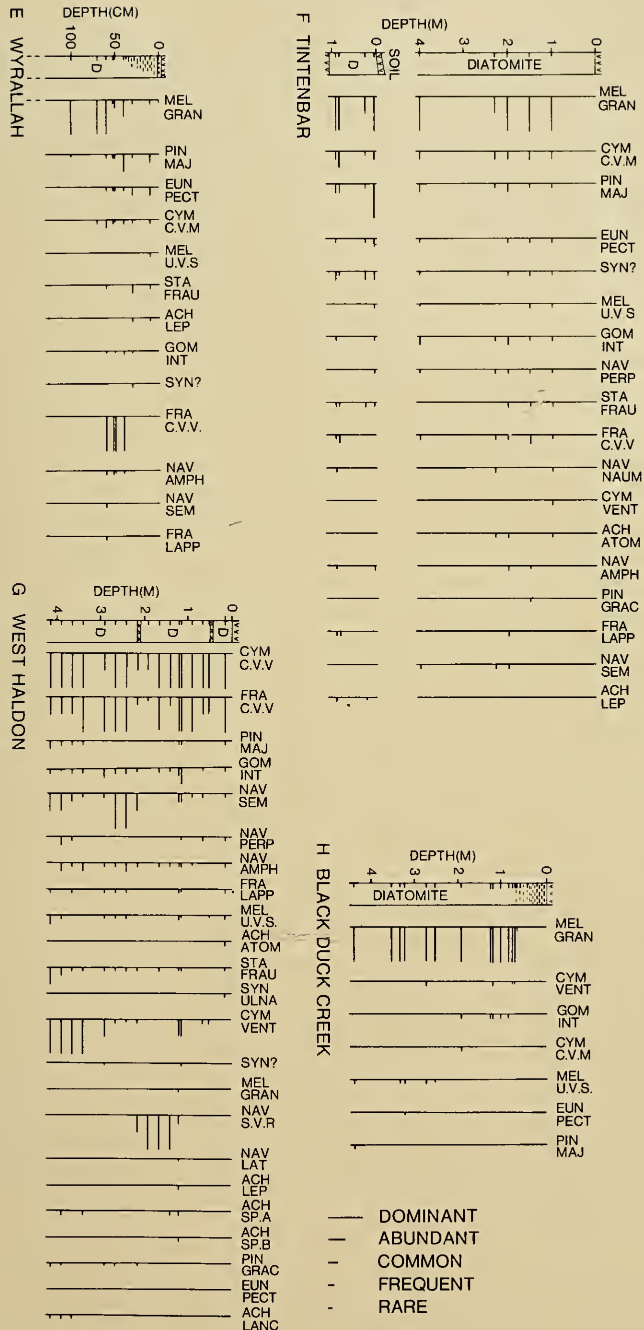



Fig. 3. A-D

*Fig. 3.* Stratigraphic sections with qualitative diatom analyses for: **A**, Bowan Downs; **B**, Middle Flat; **C**, Bells Mountain; **D**, Nandewar Range; **E**, Wyrallah; **F**, Tintenbar; **G**, West Haldon; **H**, Black Duck Creek. Key: ACH LAP, *Achnanthes* sp. af. *lapidosa;* ACH SP. A, *Achnanthes* sp. A; ACH SP. B, *Achnanthes* sp. B; CYM C.V.M, *Cymbella cistula var. maculata;* CYM VENT, *Cymbella ventricosa;* EUN PECT, *Eunotia pectinalis;* FRA C.V.V., *Fragilaria construens* var. *venter;* FRA LAP, *Fragilaria lapponica*; FRA LEPT, *Fragilaria leptostauron;* FRA L.V.D, *Fragilaria leptostauron* var. *dubia*; GOM INT, *Gomphonema intricatum;* MEL GRAN, *Melosira granulata*; MEL G.V.C, *Melosira granulata* var. *curvata*; MEL SP. A, *Melosira* sp A; MEL U.V.S., *Melosira undulata* var. *spiralis*; NAV AMPH, *Navicula amphibola*; NAV LAT, *Navicula* sp. af. *laterostrata*; NAV NAUM, *Navicula naumannii;* NAV PERP, *Navicula* sp. af. *perpusilla*; NAV SEM, *Navicula seminuloides*; NAV S.V.R, *Navicula seminuloides* var. *rhombica*; NIT SCAL, *Nitzschia scalaris*; PIN GRAC, *Pinnularia graciloides*; PIN MAJ, *Pinnularia* sp. af. *major*; STA FRAU, *Stauroneis frauenfeldiana;* SYN ULNA, *Synedra ulna;* SYN?, cf. *Synedra* sp.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CYM VENT
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EUN PECT
PIN MAJ
DOMINANT
ABUNDANT
COMMON
FREQUENT
RARE

Fig. 3. E-H

bous, limnophilous and planktonic. *Fragilaria lapponica* has been described by Abbott and Van Landingham (1972) as epiphytic and therefore probably indicative of shallow water or nearness of swamp or marsh land to the lake in which the diatoms were deposited. Hustedt (1959) described the habit of *F. leptostauron* as benthic, commonly found in the littoral region of freshwater bodies. Foged (1978) collected *Achnanthes lanceolata* from rivers and creeks with both stagnant and running water, and with pH ranges from neutral to slightly acidic. *Cymbella cistula* var. *maculata* appears to be an epiphytic species and is indicative of shallow water somewhere in the area of deposition. *Cymbella ventricosa* is a tube-dwelling, epiphytic taxon more common in shallow streams and creeks than in lakes or ponds. Hustedt (1966) described *Navicula seminuloides* as a tropical freshwater form.

Due to the obvious environmental control of non-marine diatom floras, we are cautious about drawing any biostratigraphic conclusions. Deposits with the same estimated age, e.g. West Haldon and Black Duck Creek, may show considerable differences in both number (Table 1, Fig. 2) and kinds (Table 2) of taxa present; in fact without the clear-cut information on their correlative stratigraphic positions (see Thomas and Gould, 1981), evidence for the equivalence of the West Haldon and Black Duck Creek deposits would be substantially lacking on the basis of the diatom floras alone. There is considerable variability in the total number of taxa from each locality (Table 1, Fig. 2). The West Haldon assemblage, one of the oldest, compares well with that from the present day eutrophic pond alongside the Murray River near Mannum; however the living assemblage has more genera and so could be considered a "richer" flora. Both West Haldon and the Murray River pond have a far greater number of taxa than found in the oligotrophic Lake Picton or the younger fossil deposit at Lillicur. Much of the variation in the diatom floras can be attributed to differences in environment of the lakes, rather than broader scale climatic changes or geological activity, although the latter were likely to be responsible for much of the local vertical variability as evidenced by the effects of sandstone and tuff layers in the diatomite (e.g. Fig. 3B, D). If there is a trend shown by the species data it is towards a reduction in the number of taxa with time, somewhat the reverse of what might be expected if non-marine diatoms were initially immigrants from marine environments in the early Tertiary.

We conclude that the biostratigraphy of isolated non-marine diatomites is not feasible beyond the determination of deposits of similar palaeoecological heritage. Since the deposits which are presently mined in Eastern Australia are those of low diversity, largely planktonic assemblages, like Middle Flat, Black Duck Creek, and Chalk Mountain, this could be of some commercial importance; the Bells Mountain deposit which has been extensively worked exhibits a higher diversity of taxa (Fig. 3C) but the majority are planktonic (mostly *Melosira* spp.) and it can be included in this commercially viable group. Other deposits, composed of predominantly benthic orientated taxa (Fig. 3A, D-G), display the presence of non-diatomaceous material such as clay minerals and sponge scleres.

## Acknowledgements

Thanks are due to Dr J. B. Jones, Geology Department, University of Adelaide for supplying the Lillicur samples, to Mr S. Stone, Botany Department, University of Adelaide for supplying the sample from the Murray River pool, and to Dr P. A. Tyler, Botany Department, University of Tasmania, for the Lake Picton sample. This study was carried out at the University of New England largely due to support from A.R.G.C. Grant E76/15608 to R. E. Gould.

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NOTE: The references listed here include only those additional to the ones in Thomas and Gould (1981).


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